Ecological Economics 188 (2021) 107108

Contents lists available at ScienceDirect

Ecological Economics

journal homepage: www.elsevier.com/locate/ecolecon

Analysis

Nutrient load compensation as a means of maintaining the good ecological status of surface waters

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ARTICLE INFO

Keywords:
Nutrient load compensation
Weser ruling
Water framework directive
Water quality modeling

ABSTRACT

We examine how nutrient load compensation could help a firm expand its production when production is a source of nutrient loads, threatening the ecological status of a water body. We ask whether compensation is technically feasible and whether it can be made in an ecologically sustainable way. Credits for compensation may be provided by point or nonpoint sources. We apply our approach to the case of Finnish Lake Kallavesi, where the Supreme Administrative Court, based on the Water Framework Directive, refused an environmental permit for a plan to build a large pulp mill. We employ a lake nutrient response model to determine water quality using probabilistic analysis of the ecological status of the lake. The supply potential of phosphorus credits from point sources was too low to keep the lake in good ecological status with at least 80% probability and must be complemented by credits from agricultural nonpoint sources. Using a trade ratio of 1:1.2 to reflect uncertainty on credits from nonpoint sources suggests that the reduction in agricultural phosphorus loading would suffice on its own to ensure the good ecological status by 90% probability. The cost of buying nutrient reduction credits would be at most 2% of the investment.

1. Introduction

The ecological status of surface waters in the EU has not improved as originally planned in the Water Framework Directive (WFD). The WFD requires water bodies in the EU to achieve good ecological status by 2027 and additionally requires that the status of no water body shall deteriorate (2000/60/EC). Since 2013, the Weser ruling (C-461/13) by the European Court of Justice gave the WFD a high standing by dictating that its objectives are legally binding. In the spirit of the WFD, deterioration here refers to a quality reduction in any of the indicators included in the definition of the ecological status of water bodies. These indicators include biological variables, such as phytoplankton, macrophytes and phytobenthos, which are especially sensitive to nutrient loads, as well as phosphorus and nitrogen directly (Lyche-Solheim et al., 2013; Dudley et al., 2013). Therefore, no increase in production causing water pollution is allowed if the increase in pollution weakens any indicator of water quality (see more from, e.g., Paloniitty, 2016, and Paloniitty and Kotamäki, 2021).

The Weser ruling provides a true challenge for firms wanting to expand or for new firms entering the market in cases where production causes nutrient loading and water quality is at risk. What kind of opportunities do new and expanding firms have in this situation? Ideally, the firm would invest in full water recycling so that the Weser ruling would not cause any problems. Unfortunately, this is seldom a possibility. Another option is to increase the abatement of nutrients to very high levels, which leads to gradually increasing costs. A third option is to reduce nutrient loading by decreasing the scale of the planned polluting production. As a drawback, this may often also reduce profits, threatening the whole investment. Therefore, a fourth option for these firms is to finance nutrient load reductions in other firms located in the same water body to the extent that this reduction fully compensates for the change in water quality caused by the nutrients from the expanding or new firm. Although not yet legally allowed in Finland but provided that it is made feasible, these firms could buy nutrient reduction credits to maintain the current water quality and expand their production. For bought nutrient reduction credits, it must generally hold that credits are real, verifiable, additional, and enforceable (Ribaudo et al., 2010). Furthermore, activities that generate credits must be new, must have been undertaken voluntarily (not legally mandated), and cannot be funded by other conservation incentive programs (Shortle, 2013).

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https://doi.org/10.1016/j.ecolecon.2021.107108
Received 7 September 2020; Received in revised form 28 May 2021; Accepted 28 May 2021
Available online 2 June 2021

In this paper, the term *nutrient load reduction* unit refers to a permanent (or long-term in the case of nonpoint sources) reduction of nutrient loading below the baseline, business as usual or regulator-set level. This reduction produces *nutrient reduction credits*, which, once verified, are units that can be sold. *Nutrient load compensation* refers to the use of these credits to compensate for the increase in nutrient loads by the investing firm either partially or fully. Nutrient load compensation is based on a trade between the investing firm (the buyer) and the firm producing nutrient reduction credits (the seller) with the goal of keeping water quality in good ecological status (or at least not worsening the status). Provided that the seller receives a payment that at least covers the production costs of the nutrient reduction credits, it is profitable for the seller to produce them in the market. Thus, provided that there are enough credits for sale, the investing firm could compensate for the increase in loading by buying credits to ensure that water quality does not deteriorate. For the investing firm, important questions are how great the supply of nutrient reduction credits is and at what price credits can be bought. For the regulator, the main questions are how reliably water quality impact can be assessed, how large the risk of not achieving the good status is acceptable, and what status nutrient load compensation can be given.

The idea of nutrient load compensation is relatively new, although well-known from climate policy. Multiple firms regard carbon neutrality as an important part of their environmental responsibility. Additionally, discussions on ecological compensation to stop biodiversity loss are widespread, and in the US, ecological compensation is mandatory for development projects in wetlands and streams (see, e.g., McKenney and Kiesecker, 2010). Producing nutrient reduction credits for compensating water pollution currently takes place in water quality trading (WQT) programs, which concern phosphorus, nitrogen and sediment, which are located mostly in the US (Selman et al., 2009). Many of these programs impose mandatory policies via a cap on point sources and allow voluntary participation for nonpoint sources (for reviews on WQT schemes in the US, Canada, Australia and New Zealand, see Shortle, 2013 and Selman et al., 2009). A special form of water quality trading is the credit offset trading (COT) scheme. In this scheme, point sources may buy nutrient reduction credits from other regulated point sources or nonregulated nonpoint sources to comply with the regulation when the point source's own abatement costs are too high (King and Kuch, 2003; Shabman and Stephenson, 2007; Woodward and Kaiser, 2002). Therefore, COTs provide a type of "regulator-approved" trading (Keeler, 2008; Morgan and Wolverton, 2008). This mechanism comes close to the nutrient load compensation schemes we are examining in this paper. However, compliance is not always the motivation for compensation. Very recently, some firms have announced nutrient (or phosphorus) neutrality as their environmental goal (see, for instance, John Nurminen Foundation, 2016), and neutrality is pursued with nutrient load compensation. Thus, a deeper examination of nutrient load compensation is more than warranted.

In this paper, we examine how nutrient load compensation could work as a solution to an expanding or new firm when it must fulfill the requirement that water quality in a water body in question is not allowed to decrease. We devote special attention to how to make compensations in an ecologically sustainable way. An empirically important question, albeit dependent on concrete cases, is whether such compensation is actually available. This relates to the challenge of organizing compensation in aquatic environments, which is much more difficult than for greenhouse gas (GHG) emissions. While the location of the credit provider does not matter at all for GHG emissions, the location of both the expanding firm and nutrient reduction credit suppliers matter a lot, as nutrients flow and spread in waterways (in economic terms, GHG emissions are global pollutants and nutrient loads are regional pollutants). Thus, the location and spreading of nutrients should be considered when determining the size of the required compensation and location may be the ultimate source of credit scarcity.

A further issue to consider relates to the origin of credits. Credits from point sources reflect a reduction in nutrient loading, which is certain. In contrast, credits from agricultural nonpoint sources are subject to uncertainties due to the stochastic nature of loading (Griffin and Bromley, 1982; Shortle and Dunn, 1986). The literature on point-nonpoint trading suggests using uncertainty trade ratios to cope with the uncertainty relating to nonpoint source credits (e.g., Selman et al., 2009; Shortle, 2013; Fisher-Vanden and Olmstead, 2013). In general, trade ratios address imperfect substitution between point and nonpoint polluters and are intended to translate emissions from different sources into water quality equivalents. The most typical ratio in US point-nonpoint trading has been 2:1; that is, to offset one unit of pollution, a point source must buy two credits from nonpoint sources (Shortle et al., 2021).[1]

We develop a theoretical framework to describe the problem, including the planned nutrient pulse, the expanding firm's abatement behavior, potential suppliers of offsets, the spreading of the loads in a waterbody, and the matching of the nutrient reduction credits to the nutrient pulse. We determine the choice of an investing firm given its abatement cost function and offset price. We apply our framework to a real case in Finland. In Eastern Finland, a forest firm has been planning to build a large pulp mill on the shore of Lake Kallavesi, which is in good ecological status. The planned pulp mill is, however, very large, and although efficient, it would considerably increase nutrient loads to Lake Kallavesi (Pöyry, 2015). One must assess whether the increase in nutrient load threatens the good ecological status of the lake. Due to this threat, the Supreme Administrative Court has not given it an environmental permit (SACF, 2019:166). Thus, we empirically examine whether providing full compensation for the increased nutrient load by buying nutrient reduction credits from other polluters would aid in fulfilling the non-deterioration and precautionary principles and other requirements of environmental permitting. We use a nutrient load response model of a lake (the lake load response (LLR) model of Kotamäki et al., 2015) to estimate the amount of credits needed to avoid risking the good ecological status of Lake Kallavesi. The LLR model presents outcomes concerning classes of ecological status as probabilities of belonging to a given class (to the good class in our case). We will discuss the acceptable probability and the possibilities of combining voluntary nutrient load compensation in the current water policy structure safely so that water quality can be maintained and expanding production can become possible.

The rest of the paper is organized as follows. Section 2 is devoted to the theoretical framework. Section 3 introduces the empirical data and modeling, and Section 4 presents the results of the case study calculations. Section 5 provides our conclusions.

2. Theoretical framework

In this section we define the demand and supply of nutrient reduction credits. We start by providing a schematic presentation of the framework in Fig. 1. It illustrates a water body, in this case a lake, which receives water flow from upstream and releases water downstream. The lake itself works as a large stock of water with a stable water content. A new or expanding firm is in location r and its effluent affects the water quality downstream from its location (illustrated by the black arrow). Four potential suppliers of nutrient reduction credits are depicted in the figure: three upstream (the gray arrows) and one downstream (the blue arrow). Only the three upstream point sources supply credits, as their effluents impact the whole area where the expanding firm is polluting.

Suppose now that the firm in location r increases nutrient loads by an amount X. To compensate for the increase in nutrients in the lake downstream of r, it buys nutrient reduction credits from, for instance, suppliers 1, 2 and 3. Given the hydrological processes, the reduction in

[1] Using trade ratios greater than one has been criticized as they work like a tax on point source purchases of nonpoint credits (Horan and Shortle, 2005).

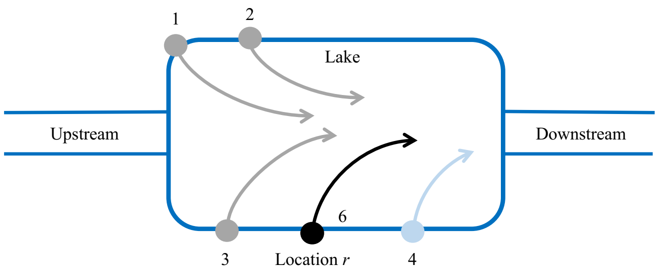

Fig. 1. Schematic representation of the determination of a sufficient number of nutrient reduction credits.

nutrients at the source does not mean an equal reduction of nutrients at location *r*. Therefore, one has to determine the delivery ratio, which is denoted by β ($\leq$1), which indicates the share of one unit of load reduction (A) at the source entering location *r*. For nutrient reduction credits originating from nonpoint sources, the uncertainty trade ratio is denoted by α, with $\alpha > 1$ for nonpoint sources and $\alpha = 1$ for point sources. The firm may have possibilities to increase its own abatement, denoted by *a*. Thus, for the upstream point and nonpoint sources (and the firm's own abatement) to fully compensate for the increase in *X*, one must have the following (with $i = 1, \ldots n$ indicating the point and nonpoint sources supplying credits):

$$\sum\nolimits_{i=1}^{n} \frac{\beta_i}{\alpha_i} A_i + a \geq X. \tag{1}$$

While Eq. (1) provides the physical requirement for nutrient load compensation, this reduction must also be feasible in economic terms, that is, the payment for nutrient reduction credits must cover at least the costs of providing these credits. Thus, we need to determine the supply potential, demand and payment for compensation.

Suppose that it is technically feasible to fulfill Eq. (1), even though this need not always be the case. The new or expanding firm's possibility of obtaining the required credits depends on the abatement costs, C (with $C'(A) > 0$ and $C''(A) > 0$), of the potential credit suppliers and the price of credits. Let q denote the price of offsets; then, the economic problem of any potential offset supplier is to maximize the revenue from additional reduction of nutrients at location *r* as follows:

$$max\ qA_i - C_i(A_i) \tag{2}$$

The first-order condition for the abatement by supplier i is $q - C_i'(A_i) = 0$, indicating that the supplier increases abatement from the baseline level up to the point where marginal revenue from nutrient reduction credits equals their marginal production (abatement) costs. The supply of credits as a function of price and abatement technology can then be expressed as follows:

$$A_i = \frac{q}{C_i'}. \tag{3}$$

The properties of this credit supply function are $\partial A_i/\partial q > 0$, indicating that the supply of credits increases with credit price.

For the firm requiring nutrient reduction credits, we make two assumptions. First, its abatement technology is the best available technology (BAT), meaning that no technological options are available to further reduce effluents ($a = 0$). Thus, the firm must compensate for all remaining emissions. This leads to a vertical demand curve for credits. Alternatively, given that the largest abatement that is technically possible exceeds the abatement achieved with the ordinary BAT, the firm can increase abatement, albeit at a high cost ($C(a)$, $a > 0$). In this case, the firm must compare the higher abatement costs against the credit costs. Let *a* denote abatement beyond the "normal" abatement and q continue to be the price of credits at point *r*. The firm minimizes its costs from abating emissions and buying credits, $C(a) + q\sum_{i=1}^{n} A_i$, by accounting for the requirement in Eq. (1). The interior solution for the firm's own abatement is defined by $C'(a) - q\frac{\alpha_i}{\beta_i} = 0$. The firm equates its marginal costs to the credit price defined at the compensation site via transfer of emissions and the type of supplier (point or nonpoint source). This choice also defines the amount of credits bought. Note that if all credit suppliers are point sources the condition reduces to $C'(a) - q/\beta = 0$. For abatement incentives, the firm's abatement increases with credit price ($da/dq > 0$) and with the uncertainty trade ratio ($da/d\alpha > 0$), and decreases with the delivery ratio ($da/d\beta < 0$). The implication of this result is obvious: if a firm has abatement possibilities at high costs, it abates more the higher the price of the credits. This means that the possibility of using nutrient reduction credits does not need to reduce a firm's incentives to abate pollution. If own abatement is not feasible at all, the firm's costs from credits are simply $q\sum_{i=1}^{n} A_i$.

We now apply this simple model of nutrient reduction credits to our empirical case, Lake Kallavesi. We determine the increase in nutrient loads, impacts on water quality and required nutrient load compensation.

3. Case study of Lake Kallavesi: water quality change and phosphorus offsets

3.1. Description of Lake Kallavesi

Lake Kallavesi is located in Eastern Finland, surrounds the city of Kuopio and is the largest lake water body in the North Savo region. The surface area of the water body is 310 km^2, the mean depth is 9.7 m, and the maximum depth is 75 m. According to the WFD status class assessment, the current overall ecological status of Lake Kallavesi is good (Vallinkoski et al., 2016). For the nutrient conditions in the lake, the average phosphorus concentration (17 μg/l) does not exceed the phosphorus criteria of the large humic lake type (25 μg/l) and the phosphorus status class is good. Because the average nitrogen levels (710 μg/l) in the lake are above the nitrogen limit (600 μg/l), the nitrogen status class is moderate. The surrogate of phytoplankton biomass, chlorophyll-*a*, has a status class of good, as the average concentration (8 μg/l) does not exceed the good status class limit (11 μg/l).[2] The water quality criteria in Finland are set based on EU's WFD guidance (EC, 2003) and the Finnish national classification system (Aroviita et al., 2012). The quality standards are based on the amount of deviation from the undisturbed/natural condition and they depend on the lake's natural type. The national lake types in Finland are defined by the lakes' surface area, altitude, mean depth, color and retention time (Pilke, 2012) which is in line with the EU level lake typology (Lyche-Solheim et al., 2013).

The nonpoint nutrient sources from the lake's catchment (16,270 km^2), such as the nutrient loads from agriculture, forestry and natural background loading, compose a majority of the lake's overall loads (Vallinkoski et al., 2016). Point sources include 11 wastewater treatment plants (WWTPs) with phosphorus loads of 2.3 tons and nitrogen loads of 400 tons annually (see Table 2), while phosphorus loads from other point sources (many related to peat production areas) amount to approximately 3.4 tons annually (YLVA, 2019).

A pulp firm (Finnpulp) planned to invest in a large pulp mill and thereby increase phosphorus loads to the lake by 20 kg per day, according to the environmental impact assessment (Pöyry, 2015). This would mean an increase of 7.3 tons annually into the lake. Compared to other sources, the planned investment would considerably increase phosphorus loading. The key issue relating to this plan is whether the increased load would lead to a worsening of the water quality in the lake from good ecological status. If this happens, phosphorus compensation

[2] Please note, that chl-a is not the only possible metrics used in the official phytoplankton status assessment (also % of harmful cyanobacteria and phytoplankton composition/trophic index). The "chl-a status" is used here due to limitations in the data and modeling.

might be the means of keeping water quality unchanged and receiving environmental permit required to build the plant.

3.2. Nutrient response model and input data

To assess the change in water quality, we employ a probabilistic, semiempirical lake load response (LLR) model tool that has been tailored for Finnish lake management planning (Kotamäki et al., 2015). The probabilistic nature of the model means that instead of a single output value, LLR produces probability distributions of the response variables and therefore accounts for the uncertainty, or the risk, that is inevitably related to these types of model-based assessments (Refsgaard et al., 2007). LLR predicts the effect of external phosphorus and nitrogen load on the phosphorus, nitrogen and chlorophyll-*a* concentration distributions and the probabilities of WFD-related status classes with the current or additional loadings. Furthermore, LLR enables estimation of the critical loading, i.e., the maximum allowable nutrient load that a lake can tolerate without shifting from good status to moderate. Given that LLR links critical nutrient loading to probabilities of WFD status classes, the question of what constitutes acceptable probability enters social decision making. We will focus on this in the discussion section.

In the model, the in-lake nutrient concentrations are estimated as a function of the incoming nutrient loads, water outflow, sedimentation rate and lake area following the parametrization of the well-known mass-balance models (Vollenweider, 1968). It is assumed that the water body is completely mixed, there are no concentration gradients, and the nutrient concentration in the water body is equal to the concentration leaving the water body. In the LLR, the modeled nutrient concentrations (and thus the loads) are linked to the lake's biological status with a hierarchical Bayesian model of chlorophyll-*a*. Fig. 2 illustrates how the model combines inflow and outflow and links lake sediment, nutrients and chlorophyll-*a*.

As model input, LLR uses data on nutrient loads, in-lake nutrient concentrations and water outflow. For the Kallavesi case, the in-lake nutrient concentration data were collected from the open source database of the Finnish Environment Institute (http://www.syke.fi/en-US/Open_information). The water quality samples are from the 1 m surface layer from the main sampling locations from 1991 to 2017 ($n = 373$ for total phosphorus and $n = 384$ for total nitrogen). The nutrient loads and the outflow are given as annual sums normalized to daily units. The annual nutrient loads and water outflows were derived from the national-scale nutrient loading estimation tool VEMALA (Huttunen et al., 2016). The VEMALA model is an operational, national-scale nutrient loading model for Finnish watersheds. It simulates nutrient processes, leaching and transport on land and in rivers and lakes. VEMALA can simulate the water quality on a daily basis in rivers and lakes larger than one hectare in Finland and provide real-time results at

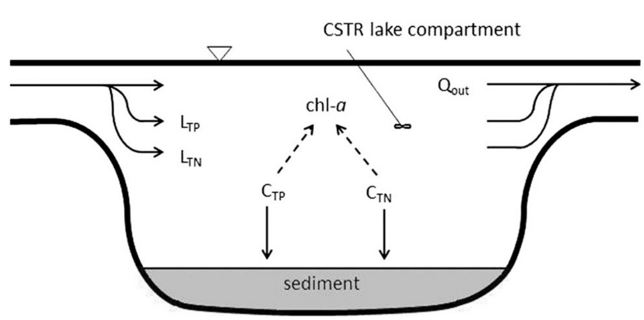

Fig. 2. Illustration of the functioning and variables of the LLR model: the incoming nutrient loads (L_{TP}, L_{TN}), water outflow (Q_{out}), in-lake phosphorus and nitrogen concentrations (C_{TP}, C_{TN}) and chlorophyll-*a* (chl-*a*). Sediment-water exchange and the size and mean depth of the lake are included in the model. The lake is represented as a continuously stirred tank reactor (CSTR). Figure from Kotamäki et al. (2015).

the user interface available from the Environmental Administration. VEMALA also analyses the contributions of the different loading sources to the nutrient loads. The input data obtained from the VEMALA model user interface are shown in Table A1 in the Appendix.

3.3. Nutrient loading response and ecological status based on the LLR model

The average long-term phosphorus load to the lake is 0.48 g/m^2/a; thus, the total average daily load is 406 kg/d. With this load, the model-estimated median total phosphorus concentration in Lake Kallavesi is 22 μg/l. The probability of at least good status was 84%, or the other way around, the risk of exceeding the nutrient standard was 16% (Fig. 3).

At 50% probability, i.e., when half of the phosphorus concentration measurements would indicate good status, the critical loading would be 0.54 g/m^2/a (459 kg/d) (Fig. 4). This is 11% higher than the average loading to the lake and would mean a 50 kg/d surplus over the "permissible" phosphorus load. However, allowing the risk to be only 10% corresponds to the critical load being lower than the current loading, leading to the need to reduce the current loading by 30 kg/d. Simulating the probabilities from 5 to 95%, the critical loads can vary between 0.44 and 0.64 g/m^2/a (or 370–548 kg/d). Therefore, depending on the risk level that the decision-maker is willing to take, the current phosphorus load levels should either be reduced, or a small increase in phosphorus load could be accepted.

Using these baseline modeling results, we can now estimate the effect of the surplus load from the pulp mill on the phosphorus concentration in the lake. The 20 kg/d addition in phosphorus load would increase the average load to 426 kg/d, which in turn would shift the median total phosphorus to 23 μg/l.

There is no generally accepted risk level associated with the precautionary principle, as it ultimately depends on public risk preferences. Choosing a low risk, say 5 or 10%, as the value that could be considered to reflect the precautionary principle, LLR modeling suggests that the required reduction in phosphorus loading to keep the Kallavesi water body in good condition should be 56 or 35 kg P/d, i.e., 20,440 or 12,775 kg/y, respectively. This means that the new pulp mill would need to find nutrient reduction credits to fully compensate for the increase in phosphorus loads (20 kg/d amounting to 7.3 tons annually). If the risk level was chosen to be 20%, the critical load would be 413 kg/d, leading to an offset of 13 kg/d, i.e., 4745 kg/y (Table 1).

To assess the ecological effects in the lake, we used the LLR to

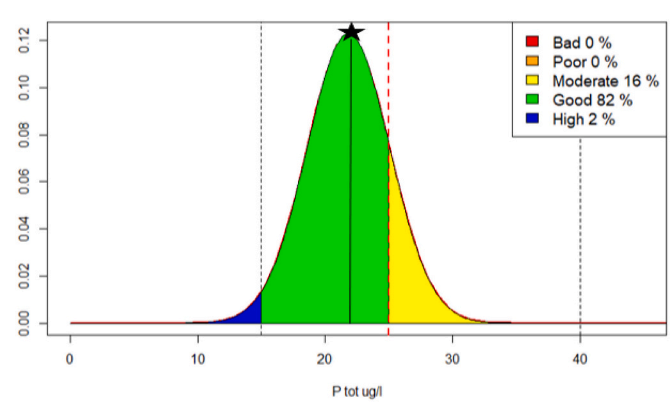

Fig. 3. Predictive probability distribution of phosphorus concentrations with average phosphorus loadings in Lake Kallavesi. Different colors denote different status classes, and the proportion of the color denotes the probability with which the status is achieved. The red dashed line is the good/moderate limit, and the star denotes the median phosphorus concentration. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

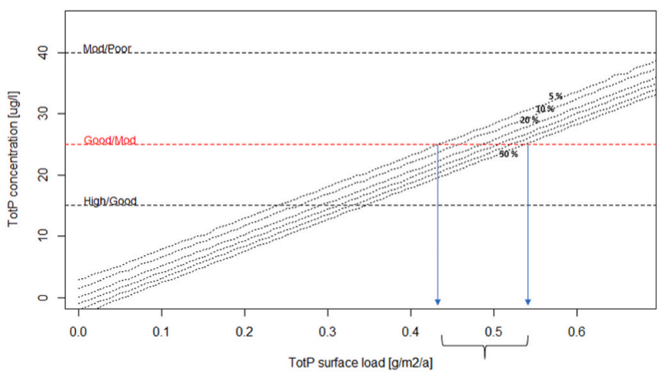

Fig. 4. Total phosphorus (TotP) concentrations as a function of phosphorus load with different risk levels (5–50%) for not maintaining good status. The blue arrows show the range of phosphorus loadings that keep the phosphorus concentration under the good/moderate limit. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

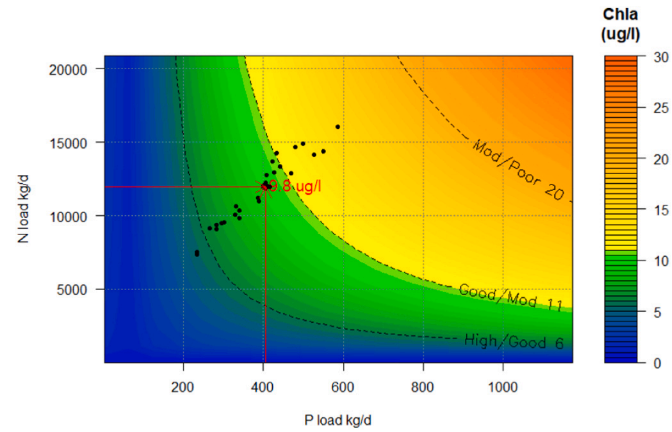

Fig. 5. Chlorophyll-*a* concentrations in Lake Kallavesi corresponding to chlorophyll-*a* status class boundaries, with different phosphorus and nitrogen loading combinations. An asterisk indicates the median chlorophyll-*a* estimate with current average nutrient loadings, and dots indicate the observed annual loadings in the lake from 1991 to 2017.

Table 1
Critical phosphorus loads (kg/d), average load with the pulp mill surplus, needed load reductions for good total phosphorus status (kg/d) and the required pulp mill nutrient load compensation (kg/d) with different risks of not reaching good status.

Probability of good TP status	Risk of not achieving good status	Critical load kg P/d	Average load with pulp mill surplus kg P/d	Load reduction for good TP status kg P/d	Required compensation kg P/d
95%	5%	370	426	56	20
90%	10%	391	426	35	20
80%	20%	413	426	13	13
70%	30%	434	426	0	0
60%	40%	455	426	0	0
50%	50%	448	426	0	0
40%	60%	477	426	0	0
30%	70%	484	426	0	0
20%	80%	505	426	0	0
10%	90%	526	426	0	0
5%	95%	548	426	0	0

estimate the chlorophyll-*a* concentrations with different combinations of total phosphorus and total nitrogen loads. The model predicted that the median chlorophyll-*a* concentration with the average long-term phosphorus and nitrogen loads is 9.8 μg/l, which stays just under the good status class boundary (11 μg/l). Assessing the simultaneous effects of nutrient loads on chlorophyll-*a* suggests phosphorus limitation, with low phosphorus loads and high nitrogen loads, and nitrogen limitation, with high phosphorus and low nitrogen loads (Fig. 5). Even a small addition in the current average phosphorus load in Lake Kallavesi would therefore lead to crossing the boundary of good ecological status, leading to moderate chlorophyll-*a* status. This is the case especially if the required probability of achieving good status would be chosen to be high.

4. Supply of nutrient reduction credits: adequacy and costs

We now shift our focus to the potential credit supply and first look at the baseline nutrient loading. We start with point sources and continue our discussion with agricultural nonpoint sources. After defining the baseline, we calculate the possible abatement and the average abatement costs separately for nitrogen and phosphorus. Finally, we discuss the potential of nutrient load compensation in the Kallavesi case study.

4.1. Baseline loading, abatement and costs

Starting with point sources, the study area contains 11 wastewater treatment plants (WWTPs) of sizes less than 1 to approximately 137,000 person equivalent (PE) (YLVA, 2019); one PE is equal to 70 g/day of BOD7 (Hautakangas et al., 2014). To estimate the supply potential and the costs of current and additional abatement, we use nutrient abatement cost functions from Hautakangas et al. (2014). Given that all but one of the WWTPs are small, the total abatement costs for phosphorus and nitrogen, respectively, are as follows:

$$C_P(x) = 82371 + 3008.7x + 8.774x^2 \tag{4a}$$

$$C_N(x) = 104982 - 2009.73x + 124.883x^2 \tag{4b}$$

where x refers to the abatement rate. For the Lehtoniemi plant in Kuopio, we use abatement costs intended for plants which are one size class larger and given by the following equations:

$$C_P(x) = 198500 + 8146.4x + 4.1665x^2 \tag{5a}$$

$$C_N(x) = 195480 + 354.589x + 230.259x^2. \tag{5b}$$

Table 2 collects the baseline data, current abatement rates, loads and our estimates on the total abatement costs of the WWTPs. We ordered the plants according to the phosphorus abatement potential, that is, the current loads. From Table 2, the current abatement rates of phosphorus are in most cases already high, and the loads are therefore relatively low, indicating a low potential for phosphorus load compensation. The possibilities for increasing nitrogen abatement are much higher, reflecting the current and much laxer abatement requirements set for the WWTPs.

In addition to the WWTPs, there are numerous other point sources around Kallavesi, outputting a total of approximately 3.4 tons P annually into Kallavesi (Vemala, 2019). The 10 largest of these sources and their phosphorus loadings are collected in Table A2 in the Appendix.

Additionally, nonpoint sources contribute considerably to phosphorus loading. The North Savo region contributes approximately 14% to Finnish beef production (OSF, 2019a); thus, much of the nonpoint phosphorus loading relates to the use of manure as fertilizer and the accumulated phosphorus reserved in soils (legacy phosphorus). The total loads from agriculture and forestry to Kelloselkä (a small part of Kallavesi) amount to approximately 47 tons of P annually (VEMALA, 2019), indicating a large potential for phosphorus reduction. This figure is, however, uncertain for many reasons: the effects of the measures reducing nutrient runoff are uncertain and this uncertainty is multiplied by the stochastic weather conditions that determine the annual nutrient loads. The prevailing agricultural support policy and its requirements

Table 2
Baseline data of the WWTPs (average values for 2017; for Kuopion vesi, the values are averages for 2018) (based on YLVA, 2019, Kuopion vesi, 2019, Hautakangas et al., 2014).

WWTP	Abatement, %		Load, kg/y		Total abatement cost, €/y	
	P	N	P	N	P	N
Kuopion vesi, Lehtoniemi	99	39	803	302,950	1,045,800	559,500
Lapinlahden Vesi Oy, village center	99	94.5	684	10,036	466,200	1,030,300
Iisalmen vesi	97.5	51.5	438	60,970	459,100	332,700
City of Kiuruvesi	91.5	16.6	228	14,320	431,100	106,000
Municipality of Sonkajärvi	85.5	4.2	87	4015	403,800	98,800
Municipality of Lapinlahti, Varpaisjärvi	98.5	62	15	2712	463,900	460,400
Runnin ympäristöhuolto Oy	89	58.5	15	417	419,600	414,800
Kuopion vesi, Kurkimäki	97	5.9	14	3139	456,800	97,500
Municipality of Leppävirta, Oravikoski	93	29	13	1203	438,000	151,700
Neuron	98	56.5	2	438	461,500	390,100
Ylä-Savo Vocational College, Peltosalmi	98	54	0	235	461,500	360,600
TOTAL			2298	400,436		

largely define the expected baseline nutrient loading, abatement and costs within agriculture, as the majority of Finnish farmers participate in the agri-environmental scheme (Hyvönen et al., 2020).

4.2. Increasing abatement from point sources

We first considered WWTPs and increased their phosphorus abatement to 99% and nitrogen abatement to 80%. Table 3 presents the reduction in phosphorus loading and the estimated total and average costs of increasing abatement in the WWTPs. In this table, the WWTPs are ordered according to their average abatement costs. Total abatement cost is the difference between the cost from the current and the new abatement efficiencies (calculated based on Hautakangas et al., 2014). Table 3 shows that the total abatement potential is 0.6 tons, which falls 6.7 tons short of the required amount of compensation. Average abatement costs vary considerably, from 27 €/kg to 5000 €/kg. Given, however, that most of the reductions are obtained from the lower part of the range, the total cost for the 0.6 t reduction remains rather low at 0.2 M€.

Even though the water quality in lakes is typically constrained by phosphorus, which is also generally the case for Lake Kallavesi, we next consider the possibility that a radical reduction in rather high nitrogen loads could improve the status class. Table 4 shows the reduction in nitrogen loads from the increase in nitrogen abatement to 80% and our estimates of the associated costs; again, the WWTPs are ordered according to their average abatement costs. The reduction potential of nitrogen is large, almost 259 t/y. The total costs of increased abatement range between WWTPs from 0.3 M€ to 1.1 M€.

We illustrate the abatement cost functions of both nutrients in Figs. 6 and 7 (the highest cost is excluded to make the lower scale visible). The total cost of any abatement level is the area under the line. For example, if a firm wanted to compensate 300 kg of phosphorus loads, it could buy 263 kg of phosphorus reduction credits with an average cost of 27 €/kg (from Iisalmen Vesi) and the remaining 37 kg of credits for 174 €/kg (from City of Kiuruvesi). Thus, the total cost of compensation of this amount would be 263*27 + 37*174 = 13,539 €.

Other point sources also provide the possibility of phosphorus load compensation, but their abatement costs are generally higher than for WWTPs. Therefore, we next examined the nutrient reduction potential

Table 3
Results of increasing phosphorus abatement to 99% in WWTPs.

WWTP	Reduction in P load, kg/y	Increase in total cost, €/y	Average abatement cost, €/kg P
Iisalmen vesi	263	7100	27
City of Kiuruvesi	201	35,100	174
Municipality of Lapinlahti, Varpaisjärvi	5	2400	486
Municipality of Sonkajärvi	81	62,500	772
Kuopion vesi, Kurkimäki	9	9500	1023
Municipality of Leppävirta, Oravikoski	11	28,100	2569
Runnin ympäristöhuolto Oy	13	46,600	3524
Neuron	1	4700	5234
TOTAL	584	201,000	

Table 4
Results of increasing nitrogen abatement to 80% in WWTPs.

WWTP	Reduction in N load, kg/y	Increase in total cost, €/y	Average abatement cost, €/kg N
Kuopion vesi, Lehtoniemi	203,622	1,138,000	6
Iisalmen vesi	35,828	410,800	11
City of Kiuruvesi	10,886	637,400	59
Municipality of Sonkajärvi	3177	644,700	203
Municipality of Lapinlahti, Varpaisjärvi	1285	283,000	220
Kuopion vesi, Kurkimäki	2472	646,000	261
Municipality of Leppävirta, Oravikoski	864	591,700	685
Neuron	236	353,400	1494
Runnin ympäristöhuolto Oy	216	328,700	1521
Ylä-Savo Vocational College, Peltosalmi	133	382,800	2877
TOTAL	258,719	5,416,000	

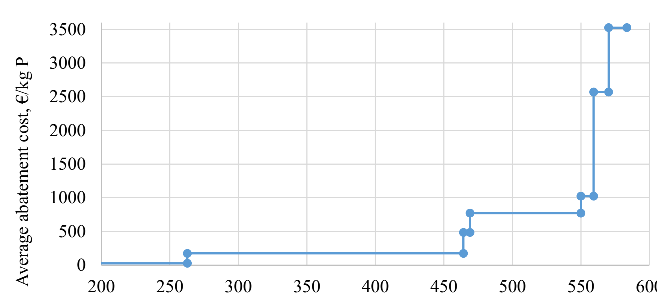

Fig. 6. Average abatement cost for reducing phosphorus loading from WWTPs.

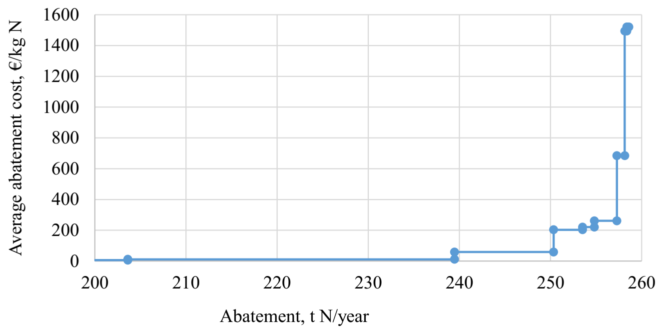

Fig. 7. Average abatement cost for reducing nitrogen loading from WWTPs.

in agriculture.

4.3. Increasing abatement from agricultural nonpoint sources

Producing nutrient reduction credits from nonpoint sources, such as agriculture and forestry, is challenging due to the stochasticity of loading and the challenge of finding agricultural practices that effectively reduce loads. Perhaps the most efficient practice is to shift fields from annual crops to long-term green fallow. This reduces erosion considerably and thereby particulate phosphorus loads and, over time also dissolved reactive phosphorus loads. Other practices relating to both animal and crop production would provide possibilities to reduce nutrient loading as well, but their reductions are not as certain as the reduction from green fallow.

Table 5 presents the potential and costs of providing phosphorus load reduction credits produced by shifting fields under cereal cultivation to long-term green fallow. Due to this change, the total phosphorus loads would decrease by approximately 0.60 kg/ha (based on Helin et al., 2006). With feed barley as the most common crop in the North Savo region (25,400 ha of cultivated and 17,400 ha of harvested area; OSF, 2019b, 2019c) and continuing single farm payment, the required yearly compensation for farmers would equal at the minimum the net profit loss from barley yield. In 2019, the profit from the average yield (3670 kg/ha; OSF, 2019c) subtracted by the variable costs amounted to 47 €/ha (Tuottopuntari 2019). Accounting also for the establishment (34 €/ha; Ervola et al., 2018) and maintenance costs (approximately 40 €/ha; Palva, 2019) of green fallow, we average and round the required payment to 100 €/ha. With this payment, the average abatement cost for reducing phosphorus loading with green fallowing is 167 €/kg. Comparing this to the values in Fig. 6 for WWTPs, this cost is relatively low. Note, however, that for WWTPs, the average cost would result in a permanent reduction in phosphorus loading (due to technological changes), contrary to agriculture, where only yearly reduction would be achieved (duration of green fallowing is dependent on the contract length).

Table 5
Yearly phosphorus loads and costs of shifting fields from cereal crop cultivation to green fallow, transaction costs and the required field area with trade ratios of 1 and 1.2.

	Value	Unit
Phosphorus load from barley[a]	0.99	kg/ha
Phosphorus load from green fallow[a]	0.39	kg/ha
Reduction in phosphorus load	0.60	kg/ha
Net profit from feed barley[b]	47	€/ha
Establishment[c] and maintenance[d] cost of green fallow	34 + 40	€/ha
Total yearly cost of green fallowing (rounded)	100	€/ha
Transaction costs: soil testing and runoff plan (once per contract)[e]	25	€/ha
Transaction costs: monitoring and negotiations (8% of payment)[f]	8	€/ha
Required field area with trade ratio 1	12	1000 ha
Required land area with trade ratio 1.2	15	1000 ha

[a] Helin et al. (2006), with erosion value of 800 kg/ha for barley.

[b] Tuottopuntari (2019).

[c] Ervola et al. (2018).

[d] Palva (2019).

[e] Lankoski et al. (2010).

[f] Monitoring 2% (Ollikainen et al., 2008), negotiations 6% (estimated value).

The compensation cost would be higher for the buyer in the presence of transaction costs. Soil tests and runoff plans needed for the agreement cost approximately 25 €/ha as a one-time cost (Lankoski et al., 2010). Additionally, negotiations and monitoring could take up approximately 8% of the per-hectare credit payment (Ollikainen et al., 2008; author estimation), i.e., the yearly compensation cost for the pulp mill would increase to 108 €/ha.

Recall the need for using trade ratios to reflect the uncertainty of nutrient reduction credits from agricultural nonpoint sources. The typical trade ratios in point-nonpoint trading have been greater than one. We employ two trade ratios: 1:1 as a benchmark and 1:1.2 to reflect the uncertainty of nonpoint loading from green fallow. This trade ratio is quite low, but it accounts for the fact that unfertilized green fallow provides a higher yearly reduction in the dissolved reactive phosphorus loading over time. With a trade ratio of 1, the pulp mill would need to buy credits from 12,000 ha to compensate for the 7.3 ton increase in the phosphorus load. With a trade ratio of 1.2, the required field area would rise to 15,000 ha.[3]

4.4. Compensation possibilities

The pulp mill can compensate its phosphorus loads by buying credits from point sources or nonpoint sources or using a combination of credits from both sources.[4] The planned pulp mill production causes 7.3 t/y of phosphorus loading. Table 6 presents the required compensation of phosphorus loads and the associated costs from WWTPs when a good ecological state of the lake must be achieved by 90% or 80% probability and assuming that the delivery ratio of credits, β, is 1 or 0.8. Under 90% probability, all loading must be compensated, and under 80% probability, most but not all loading needs compensation. Referring to Table 1, reducing the probability of achieving good ecological status to 70% or less would entail no compensations. As the maximum additional phosphorus abatement from the WWTPs is approximately 0.6 t/y, the firm could buy nitrogen reduction credits to match the required compensation. Reduction in nitrogen loading affects the ecological status of the lake, as shown in Fig. 5. The required compensation in nitrogen load is calculated using the Redfield ratio, indicating that algae uses phosphorus and nitrogen in ration 1:7.2 (Kiirikki et al., 2003), which expresses phosphorus loads as nitrogen equivalents. This facilitates determination of the required reduction in nitrogen loading. Note, that the N:P ratio varies between watersheds, and the ratio directly affects the required nitrogen compensation.

[3] Green fallow would reduce also nitrogen loading as a positive side effect, but in this case, phosphorus reduction potential is high enough. If nitrogen compensations were allowed, it would reduce the required area for credits.

[4] The pulp mill could also decrease its loads by reducing the scale of the planned production, which under BAT would reduce phosphorus loading accordingly. The results for reduced pulp mill scale are presented in the Appendix in Table A3 for the WWTPs and in Table A4 for agricultural nonpoint sources.

Table 6
Total compensation costs from the WWTPs, with delivery ratios of 1 and 0.8 and probabilities of good status class of 90% and 80%.

Delivery ratio	Good status probability, %	Pulp mill P load, tP/y	P compensation		N compensation		Total cost, M€
			Required, tP/y	Obtained, tP/y	Required, tN/y	Obtained, tN/y	
1	90	7.3	7.3	0.6	48	48	0.47
1	80	7.3	4.7	0.6	30	30	0.36
0.8	90	7.3	7.3	0.5	49	49	0.54
0.8	80	7.3	4.7	0.5	31	31	0.41

Table 7
Total compensation costs from agriculture (for 25 years with a 3% discount rate), required area for green fallowing, and the share of compensation costs from the planned pulp mill investment (1600 M€) with varying probability of maintaining good status, trade ratio and delivery ratio.

Trade ratio	Delivery ratio	Good status probability, %	Required P compensation, t/y	Required area, 1000 ha	Annual compensation cost, M€/y	Compensation cost net present value, M€	Share of cost from pulp mill investment, %
1	1	90	7.3	12	1.2	22	1.4
1	1	80	4.7	7.9	0.8	14	0.9
1.2	0.8	90	8.8	18	1.8	33	2.1
1.2	0.8	80	5.7	12	1.2	21	1.3

In Table 6, the unit cost of phosphorus load compensation is determined using the average abatement cost for each WWTP. Table 6 assumes that the pulp mill first buys as much phosphorus load compensation as possible from the WWTPs (0.6 t) and then acquires nitrogen reduction credits for the remaining compensation. If the delivery ratio is 0.8, 0.6 t of phosphorus reduction only accounts for a 0.5 t reduction at the location of the pulp mill, and in the same vein, the delivery ratio must also be taken into account for nitrogen. Thus, for a delivery ratio of 0.8, abatement and abatement costs are higher than for delivery ratio 1.

The compensation costs from phosphorus are in each case 0.20 M€. The costs from nitrogen compensation vary depending on the required credit amount: 0.27 M€ and 0.17 M€ for delivery ratio of 1 and good status probability of 90% and 80%, respectively, and 0.34 M€ and 0.22 M€ for delivery ratio of 0.8 and good status probability of 90% and 80%, respectively. The total costs of compensation are rather low with the highest estimate being 0.5 M€, i.e., 0.03% of the planned 1600 M€ pulp mill investment (Finnpulp, 2020). A shift from 90% probability to 80% probability would reduce the compensation costs by 22%. Table 6 suggests that the best policy for the pulp mill is to buy credits for full compensation and for society sticking to the requirement of at least 90% probability for achieving good ecological status of the lake. The sustainability of using nitrogen credits can, however, be challenged, as lakes are typically phosphorus constrained. Therefore, it is of interest to ask whether agriculture could provide all required phosphorus reduction credits to ensure that compensation is ecologically sustainable.

Table 7 collects the results of compensation costs from agriculture. With the trade ratio and delivery ratio set to 1, acquiring 7.3 tons of phosphorus load compensation from agriculture through green fallowing would require a total of 12,000 ha. The yearly compensation costs for the total area are 1.2 M€. We assume that the fallow contract with farmers is for 25 years giving the total present value of the compensation cost with a 3% discount rate approximately 22 M€. With a trade ratio of 1.2 and delivery ratio of 0.8, the load reduction at the compensation site from green fallowing decreases to 0.48 kg/ha, and the required phosphorus load compensation increases to 8.8 tons (i.e., 1.2 times the 7.3 t requirement), corresponding to 18,000 ha. The annual compensation cost is now 1.8 M€, and the present value of compensation for 25 years rises to approximately 33 M€. If the required probability for the good ecological status is lowered, the required compensation and the total costs also decrease (this is also the case with reduced pulp mill scale, see Table A4 in the Appendix for results). All calculated net present values of compensation costs are at most 2.1% of the planned 1600 M€ investment (Finnpulp, 2020). The land areas listed in Table 7 are large, but the associated costs for the pulp mill are quite modest. Thus, compensation would be possible in practice, at least for the lowest cost land areas. For the highest area requirement, 18,000 ha, grain cultivated areas other than feed barley may also need to be included.

When transaction costs presented in Table 5 are included in the total compensation costs, the net present value of compensation costs over 25 years would amount to 36 M€ and 23 M€ (trade ratio 1.2 and delivery ratio 0.8) with 90% and 80% good status probability, respectively. Even with the transaction costs, compensations would take at most only 2.2% of the planned investment.

The cost-efficient choice of the pulp mill under a delivery ratio of 0.8 is as follows (see Table 8): buy 0.6 t phosphorus load compensation from WWTPs with a cost of 0.2 M€ to obtain 0.5 t of credits and buy the remaining compensation from agriculture. Under a trade ratio of 1.2, this gives costs of 31 M€ under 90% probability and 20 M€ under 80% probability as a net present value over 25 years. Acquiring compensations solely from agriculture would be more costly (33 M€ and 21 M€ for 90% and 80% probabilities, respectively) since compensation from WWTPs is permanent, whereas agricultural compensation needs to be bought/paid yearly.

In light of these figures, compensation looks economically and ecologically feasible. An important caveat must, however, be made concerning slippage and leakage. Slippage refers to the possibility that a fallowing farm takes new fields in cultivation within farm boundaries or

Table 8
Cost-efficient compensation for the pulp mill with a trade ratio of 1.2 and delivery ratio of 0.8.

Good status probability	Compensation source	Compensation, tP (required area, 1000 ha)	Compensation cost net present value, M€	Share of investment, %
90%	WWTPs	0.5	0.20	
	Agriculture	8.3 (17)	31.0	
	Total	8.8	31.2	2.0
80%	WWTPs	0.5	0.20	
	Agriculture	5.7 (11)	19.5	
	Total	4.7	19.7	1.2

increases fertilizer intensity in remaining fields to compensate for the reduced crop production (Fleming et al., 2018; Lichtenberg and Smith-Ramirez, 2011, and Shortle et al., 2021). This would increase farm phosphorus loads to the lake and reduce the load reduction. Leakage refers to phosphorus load increases over the whole area due to increased demand for crops (Roberts and Bucholz, 2006; Wu, 2000, 2005). Both features would reduce the actual reduction of loads that credits would provide. Assessing slippage is in general difficult. However, entry of new fields is unlikely, as these fields would not be eligible for the single farm payment in CAP. Thus, farmers could allocate some existing field parcels to cereal crops from other uses, but this would most likely have only minor impacts on P loads. Leakage may play a larger role. The shift of 17,000 ha from feed barley to green fallow would result in a 62 million kg reduction in the local supply of feed barley, creating demand for other feed sources for the area's large beef and milk production. As a comparison, in 2018/2019 in Finland, the total amount of grains used as feed in industry was 562 million kg, and on farms, it was 1063 million kg (Natural Resources Institute Finland, 2021).

5. Discussion and conclusions

We examined how nutrient load compensation can help a firm expand its production when production causes nutrient loads threatening the ecological status of a water body. Nutrient effluents to waterways are regional emissions, indicating that nutrient load reduction at the source differs from the actual reduction at the compensation site. This was taken into account using delivery ratios. A second complicating matter related to the sources of nutrient load reduction credits. In contrast to point sources, reduction credits from nonpoint sources are uncertain and subject to stochastic variation. This was taken into account using trade ratios. The third issue related how to define the good ecological status of the water body subject to all uncertainties; we adopted a probabilistic approach.

We assessed these issues against the case of the Finnish Lake Kallavesi, where the Supreme Administrative Court denied the environmental permit for a plan to build a large pulp mill because of the risk of worsening the lake's good ecological status (SACF, 2019:166). In the chosen case, the increase in phosphorus loads from the planned pulp mill was rather high, at 7.3 t/y, threatening the goal of keeping the lake in good ecological condition with 80% probability at the minimum. In the cost-efficient solution, the pulp mill utilized the whole phosphorus reduction potential from point sources (WWTPs) and bought the rest of the credits from agricultural nonpoint sources. Credits were generated from a shift to long-term green fallow, which provides a fairly certain reduction in phosphorus loading and thus facilitates a low trade ratio. The cost of full compensation was quite low, 31 M€ in total, suggesting that compensation is a good opportunity for the pulp mill. Our findings are in line with Shabman and Stephenson (2007), who found that buying credits from nonpoint sources could allow new point source companies to enter the market when water quality objectives cannot be met by the company alone. Allowing nonpoint sources to provide credits also has the potential to lower the overall costs from nutrient load reductions.

Our analysis suggests that nutrient load compensation could play a role in investments causing nutrient loading, in tightening abatement policy, or in strict water protection, which the Weser ruling represents. There are, however, multiple economic and ecological issues that society must evaluate concerning nutrient load compensations.

Starting with economics, transaction costs impact the costs of compensation, and slippage and leakage matter greatly for the ecological integrity of compensation. Long-term green fallow is easy to establish and monitor, which keeps transaction costs low and lower than in many other possible agricultural practices, as also shown for CAP policy by Ollikainen et al. (2008). The downside of using green fallow is a clear reduction in agricultural production and an increased risk for slippage and leakage. Both tend to increase phosphorus loading and reduce the actual load reduction at the compensation site. Estimation of this impact is difficult, and the literature has not produced a clear understanding of its empirical relevance (Stephenson and Shabman, 2017). Our estimate was that in the Kallavesi case, large feed barley areas transformed to green fallow would create high demand for other feed sources for cattle and, thus, a risk for leakage outside the area.

A topic that relates to both economic and ecological impacts relates to the possibility of generating nitrogen reduction credits as compensation for phosphorus loads. Although reductions in nitrogen loading may affect the overall status class and the abatement possibilities for nitrogen are relatively high, phytoplankton growth in lakes is primarily limited by phosphorus availability (Schindler, 1977). However, nitrogen limitation, or colimitation of both phosphorus and nitrogen, can occur in certain conditions, especially on shorter time scales than in multiannual time scale and in shallow lakes (Sterner, 2008; Maberly et al., 2020). Therefore, nitrogen load compensation may be feasible in a similar setting as in Lake Kallavesi, especially if the water body is limited by both phosphorus and nitrogen or limited solely by nitrogen. Even in primarily phosphorus-limited sites, once the input of phosphorus has been reduced, it is worthwhile to explore whether further ecological benefits of reducing nitrogen exist (Maberly et al., 2020).

Concerning the ecological integrity of compensations, there is always uncertainty related to the nutrient load response model assessments, which causes risks in decision-making. We used a simple water quality model accounting only for the aggregated spatiotemporal level yet accounting for the natural variation with the probabilistic approach. Model development is always a compromise between model complexity, data availability and modeling resources. This is particularly true for lake management models, which are required to be quick to use, readily usable at new locations, and at spatiotemporal dimensions relevant for the decision-making in question (see, e.g., Schuwirth et al., 2019). In Finland and in other Nordic countries, the number of lakes (and water bodies) is very high, making it impossible to monitor all the biological quality elements in a sufficient manner, thus limiting the data availability and model complexity (Andersen et al., 2016; Hjerppe et al., 2016). The complex nature of human-environment relationships, the high natural variation in environmental conditions and the lack of empirical data all affect the uncertainty of the modeled responses (Refsgaard et al., 2007). Some of these uncertainties can be reduced, but it should be acknowledged that decisions made based on assessment results are never risk-free. Therefore, the loading response assessment should consider the uncertainty in the results, as we did in our case. Depending on the risk of violating good water quality standards that the decision maker is willing to accept, the phosphorus load compensation in the lake Kallavesi case could vary from 0 kg/y (risk 30% or more) to 7.3 t/y (risk less than 10%). The key question is what the applied probability should be in society. Usually, following a safe minimum standard is recommended in cases where uncertainty prevails (see, e.g., Heywood, 1995). This does not, however, give any specific number. Public debate on feasible criteria is needed. We calculated the critical phosphorus loads with different risk levels without making a statement of the proper risk level. This kind of procedure could be used in practice as well to showcase the relationship of loads, risks and probabilities.

The second issue relates to the spatial and temporal aspects of compensation. In our case, the lake is small and the area from which the credit supply was defined was based on a geographically rather narrow area. How much of a geographical area from the catchment can be taken for nutrient reduction credits may in most cases be decisive for the compensation potential. Another complicating factor is that the timing of the actual reduction by credits (supply of credits) often may differ from the increase in nutrient runoff (demand for credits). If compensating measures are taken only after the load increase (e.g., green fallowing is not realized immediately for agronomic reasons), it risks maintaining the current ecological status. This intertemporality of load increase and decrease could be accounted for by higher trade ratios (Cook and Shortle, 2018), or an insurance or reserve ratio could be used to set aside a fixed share of credits, building up a reserve pool (Selman et al., 2009) to prepare for various situations. In addition, the lakes' ecological status is assessed for the growing season, namely, July–August for phytoplankton and June–September for nutrients (EU, 2003); therefore, the effect of load increase or reduction might be different within different time periods.

Finding sufficient answers to the presented challenges is necessary to allow nutrient load compensation to provide solutions for investment bans due to the WFD and Weser ruling. Compensation would help in unravelling the high abatement potential of agriculture, which the present policy is not able to do. Currently, nutrient load compensation is not allowed in Finland. Enabling compensation would be one step toward more adaptive management and governance of our waters. Adaptive governance would allow more flexibility in fulfilling the requirements regarding nutrient loading reductions as well as other environmental goals.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work is a part of the research consortium "Enhancing Adaptive Capacity for Sustainable Blue Growth (BlueAdapt)", which is funded by the Strategic Research Council of Academy of Finland (Contract No. 312650 Blue-Adapt). We thank two anonymous reviewers for their helpful comments.

Additional data and results

Table A1
LLR input data for modeling of Lake Kallavesi: incoming annual nutrient loads and lake concentrations and water outflow from the lake.

Year	Nitrogen load (kg/d)	Phosphorus load (kg/d)	Nitrogen conc. (μg/l)	Phosphorus conc. (μg/l)	Water outflow (m^3s^{-1})
1991	13,364.49	440.566	557.1429	15.28571	157.945
1992	14,909.7	499.9737	697.1429	17.85714	166.814
1993	14,264.6	432.6792	682.8571	22.57143	152.842
1994	13,701.43	423.1611	630	20	145.755
1995	12,927.23	426.5212	610	18.11111	144.589
1996	10,075.53	328.4873	518.75	15.5	119.623
1997	10,632.7	330.9653	620	14.85714	123.715
1998	14,673.42	479.6687	594.2857	18.14286	168.842
1999	9499.079	294.6331	625.7143	18.85714	105.743
2000	12,763.42	406.6919	656	18.65	143.226
2001	10,364.25	339.3738	706.3636	19.09091	124.065
2002	7365.112	233.6329	659.0909	17	91.167
2003	7534.411	232.4012	650	15.09091	89.911
2004	12,857.58	468.5431	712.3077	21.46154	177.09
2005	9810.921	340.5677	841.6667	24.63636	124.545
2006	9370.142	281.9616	870.8333	21.30769	103.072
2007	12,256.19	406.0394	828.4615	21.6	155.012
2008	14,357.23	549.7275	776.6667	22.6	196.568
2009	9090.156	283.2351	754.2857	22.85714	102.037
2010	9142.134	265.725	807.1429	21	105.472
2011	9511.049	301.3674	750	16.6875	119.503
2012	16,057.64	586.88	755.7143	23.78571	214.04
2013	11,943.94	411.7861	852.8571	26.42857	139.016
2014	11,973	416.3966	769.2857	24.5	156.845
2015	14,143.18	526.2276	731.6667	23.47619	193.046
2016	10,967.3	388.2791	757.381	25.54762	151.438
2017	11,223.45	386.7345	623.8095	20.03571	154.886

Table A2
Baseline phosphorus loading from the 10 largest point sources other than WWTPs to Kallavesi (average yearly values from 2010 to 2018) (source: VEMALA).

Point source	P load, kg/y
Powerflute Oy (former Savon Sellu Oy)	2129
Terhontammi Oy, Konnuslahti fish farm	117
VAPO OY, Konnunsuo, Pyhäntä	106
VAPO OY, Kaikonsuo	84
Heinäsuon Turve Oy, Heinäsuo, Vieremä	79
VAPO OY, Pihlajasuo	49
Kuopion Energia, Rikkasuo, Kiuruvesi	48
VAPO OY, Heinäsuo and Kokkosuo	46
VAPO OY, Peräsuo/Härkäsuo	45
Kuopion Energia, Kukkosuo, Vieremä	44

Table A3
Total compensation costs from the WWTPs, with delivery ratios of 1 and 0.8 with the baseline scale of pulp mill production, for cases where this scale is reduced by 10% or 20%, and with the probability of good status class of 90% and 80%.

	Pulp mill P load, tP/y	P compensation		N compensation, tN/y	Cost from P, 1000 €	Cost from N, 1000€	Total cost, 1000 €
		Required, tP/y	Obtained, tP/y				
Delivery ratio 1, good status probability 90%							
Baseline scale	7.3	7.3	0.6	48	196	270	466
Scale reduced by 10%	6.6	6.6	0.6	43	196	241	437
Scale reduced by 20%	5.8	5.8	0.6	38	196	211	407
Delivery ratio 1, good status probability 80%							
Baseline scale	7.3	4.7	0.6	30	196	167	363
Scale reduced by 10%	6.6	4.7	0.6	30	196	167	363
Scale reduced by 20%	5.8	4.7	0.6	30	196	167	363
Delivery ratio 0.8, good status probability 90%							
Baseline scale	7.3	7.3	0.5	49	196	344	540
Scale reduced by 10%	6.6	6.6	0.5	44	196	307	503
Scale reduced by 20%	5.8	5.8	0.5	39	196	270	466
Delivery ratio 0.8, good status probability 80%							
Baseline scale	7.3	4.7	0.5	31	196	215	411
Scale reduced by 10%	6.6	4.7	0.5	31	196	215	411
Scale reduced by 20%	5.8	4.7	0.5	31	196	215	411

Table A4
Total compensation costs from agriculture (for 25 years with a 3% discount rate), required area for green fallowing, and the share of compensation costs from the planned pulp mill investment (1600 M€) with varying pulp mill scale, probability of maintaining good status, trade ratio and delivery ratio.

	Required P compensation, t/y	Required area, 1000 ha	Annual compensation cost, M€/y	Compensation cost net present value, M€	Share of cost from pulp mill investment, %
Trade ratio 1, delivery ratio 1, good status probability 90%					
Baseline scale	7.3	12	1.2	22	1.4
Scale reduced by 10%	6.6	11	1.1	20	1.2
Scale reduced by 20%	5.8	10	1.0	17	1.1
Trade ratio 1, delivery ratio 1, good status probability 80%					
Baseline scale	4.7	8	0.8	14	0.9
Scale reduced by 10%	4.7	8	0.8	14	0.9
Scale reduced by 20%	4.7	8	0.8	14	0.9
Trade ratio 1.2, delivery ratio 0.8, good status probability 90%					
Baseline scale	8.8	18	1.8	33	2.0
Scale reduced by 10%	7.9	16	1.6	29	1.8
Scale reduced by 20%	7.0	15	1.5	26	1.5
Trade ratio 1.2, delivery ratio 0.8, good status probability 80%					
Baseline scale	5.7	12	1.2	21	1.3
Scale reduced by 10%	5.7	12	1.2	21	1.3
Scale reduced by 20%	5.7	12	1.2	21	1.3

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